Stabilization of Interchange Modes by Rotating Magnetic Fields (RMF)

Houyang Guo, Alan Hoffman, Richard Milroy, Ken Miller, George Votroubek

Redmond Plasma Physics Laboratory
University of Washington

US-Japan Santa-Fe
Santa Fe, NM
Sept. 14-16, 2004

Introduction

- **High-β linear confinement configurations are intrinsically unstable to interchange or fluting modes due to unfavorable field line curvature.**

- **In FRCs, the ions generally carry much of the diamagnetic current, and the concomitant plasma rotation produces a much more dominant instability drive force.**

- **The dominant instability under these conditions is the rotational n=2 instability, which is nearly ubiquitous in the θ-pinch formed FRCs.**

Outline

- **Rotational instabilities** in θ-pinch formed FRCs

- Ion rotation and structure of rotational modes in RMF driven FRCs in TCS

- Evidence of stabilizing effects from RMF

- Influence of RMF antenna geometries

- Summary and conclusions

FRC stability

Side View

End View
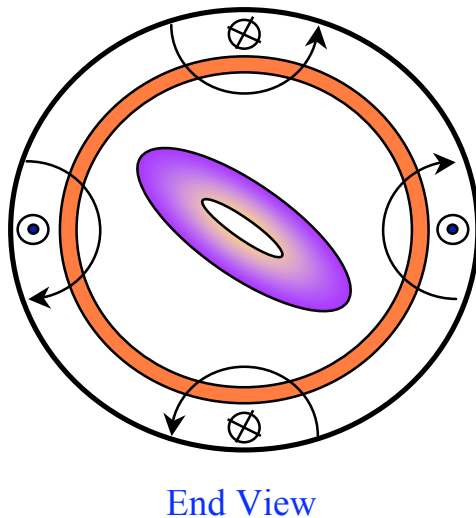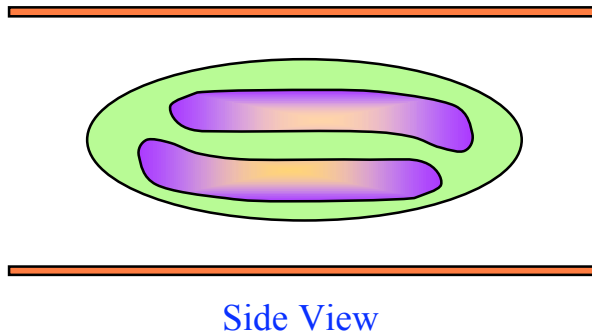
- **Internal tilt** starts out as an axial n=1 shift mode
  - – Highly unstable, predicted by MHD
  - – But has not been observed experimentally

- **Rotational n=2 mode** is the dominant global instability observed experimentally
  - – Driven by centrifugal force due to plasma rotation
  - – Leading to Rayleigh-Taylor type instability

Rotational instabilities in θ-pinch formed FRCs

- **Simple Rayleigh-Taylor analysis:**

$$\_ \sim \_(r)\, e^{i(n\theta - \omega t)}$$

$$\omega^2 = -g/[\delta_\rho(1/4\,\delta_\rho{}^2 + (n\pi/h)^2 + k^2)] < 0,$$

$$g = \Omega^2 r,\ k = n/r$$
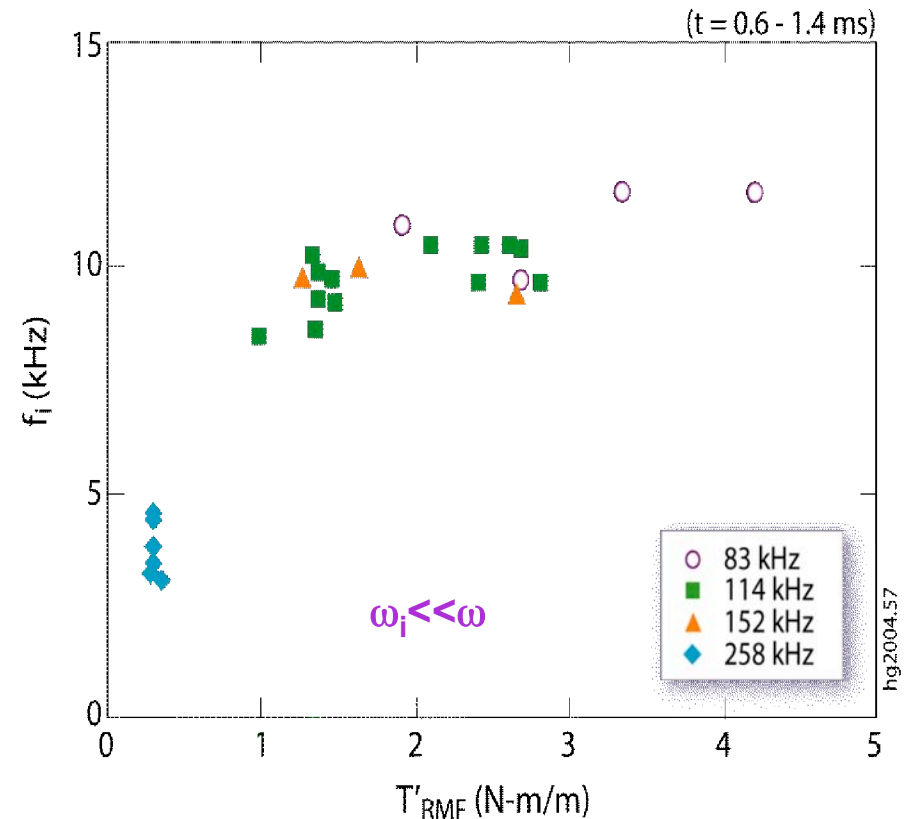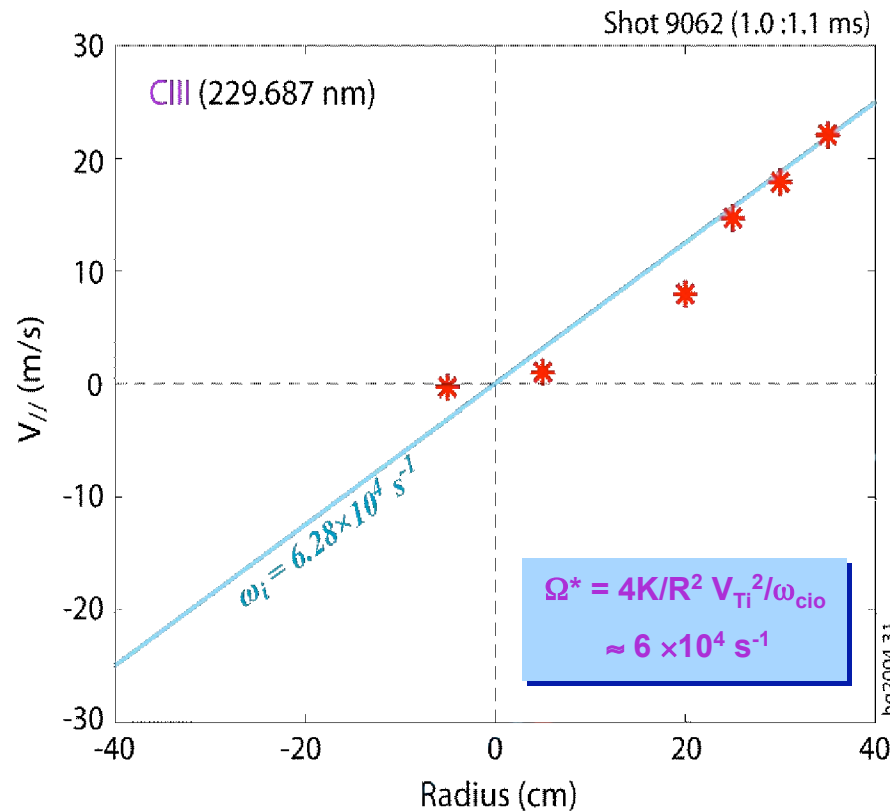
Growth rate: $\gamma \approx (g/\delta_\rho)^{1/2}$

- **MHD with FLR corrections** $\Rightarrow$

Instability threshold: $\alpha \equiv \Omega/\Omega_i^* > 1$
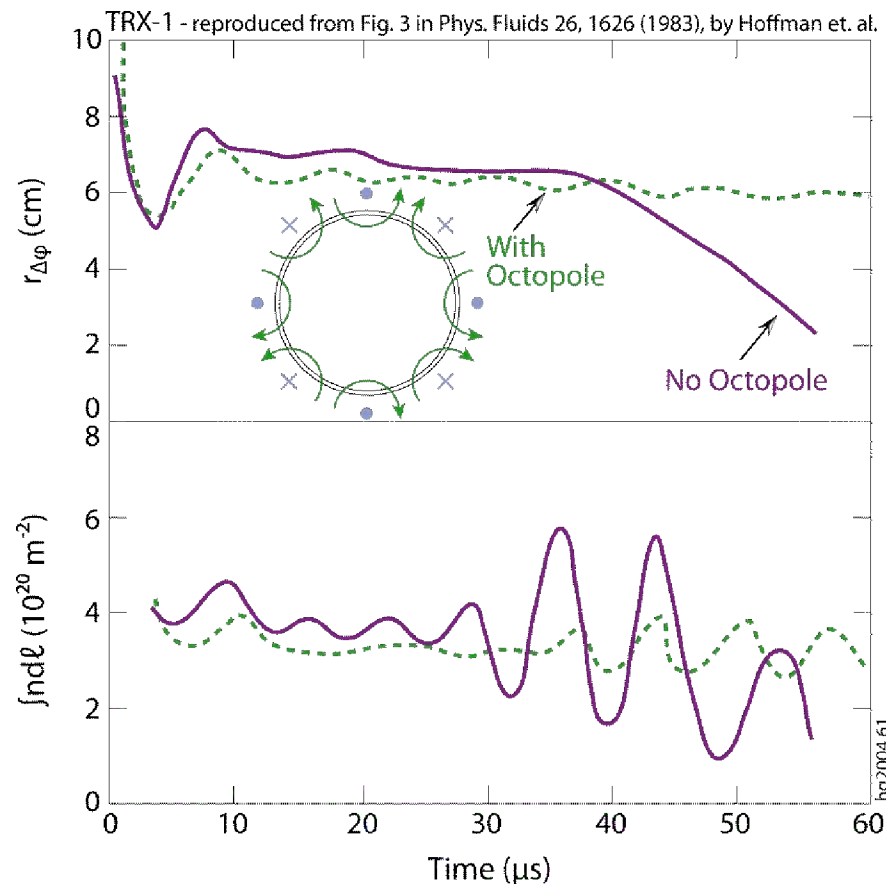
- **Static multipole stabilization:**

$$B_m{}^2/2\mu_o >\_ \langle\rho\rangle\Omega^2 r_s{}^2$$

Ion rotation in RMF driven FRCs

Shot 9062 (1.0 :1.1 ms)

CIII (229.687 nm)

$\omega_i = 6.28 \times 10^4 \, s^{-1}$

$$\Omega^* = 4K/R^2 \, V_{Ti}^2/\omega_{cio}$$
$$\approx 6 \times 10^4 \, s^{-1}$$

$V_{//}$ (m/s) vs Radius (cm)

hg2004.31

(t = 0.6 - 1.4 ms)

f_i (kHz) vs T'_{RMF} (N-m/m)

$\omega_i << \omega$

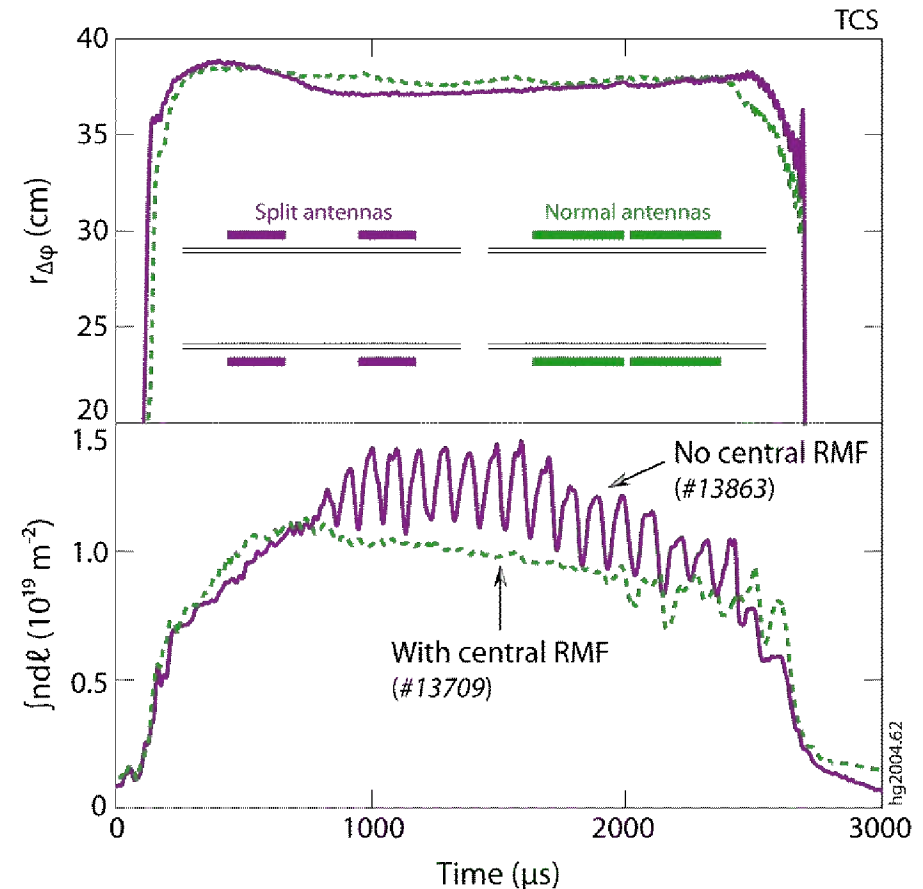|	
○	83 kHz
■	114 kHz
▲	152 kHz
◆	258 kHz

hg2004.57

- **Plasma spins up in electron diamagnetic direction due to the RMF applied torque, *contrary to θ-pinch formed FRCs*.**

- $\omega_i \geq \Omega^*$ **for most FRCs except at high ω due to reduced RMF torque.**

Rotational instabilities in θ-pinch & RMF formed FRCs

TRX-1 - reproduced from Fig. 3 in Phys. Fluids 26, 1626 (1983), by Hoffman et. al.

With Octopole

No Octopole

hg2004.61

TCS

Split antennas   Normal antennas

No central RMF (#13863)

With central RMF (#13709)

hg2004.62

- **_-pinch FRC: n=2 is destructive**
- **Usually stabilized by mulipole fields**

- **RMF FRC: n=2 is non-destructive**
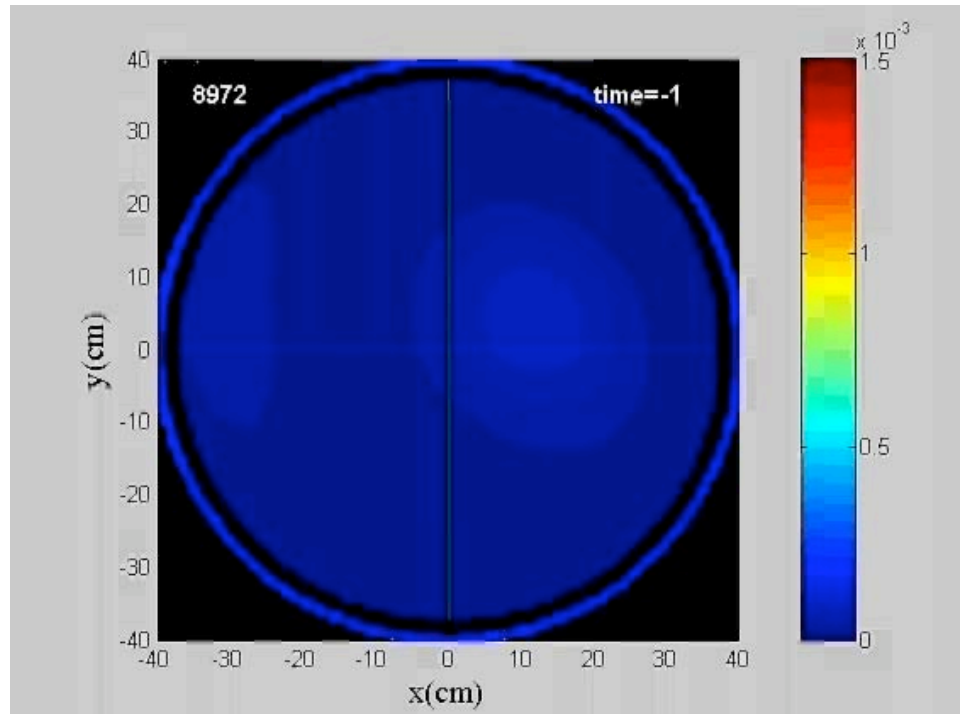- **Stable when RMF antennas cover central portion**

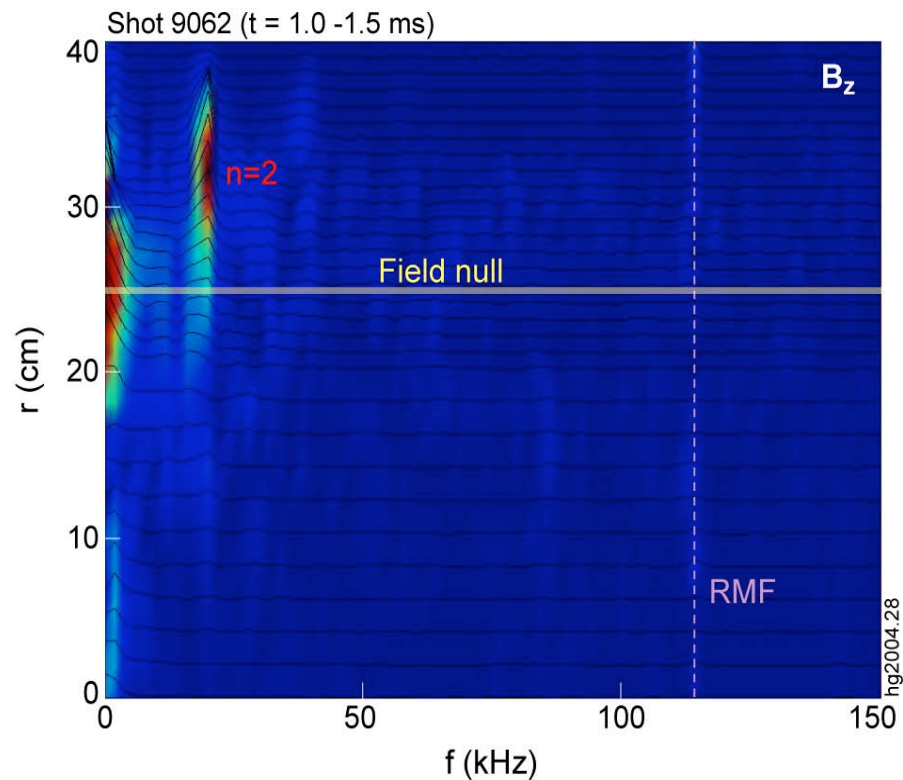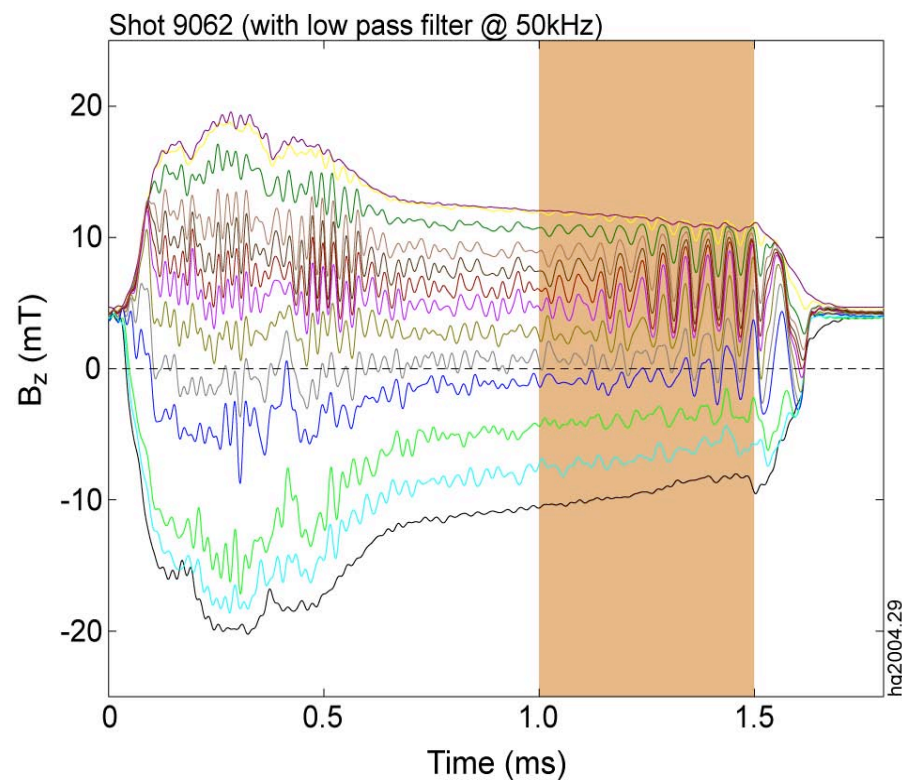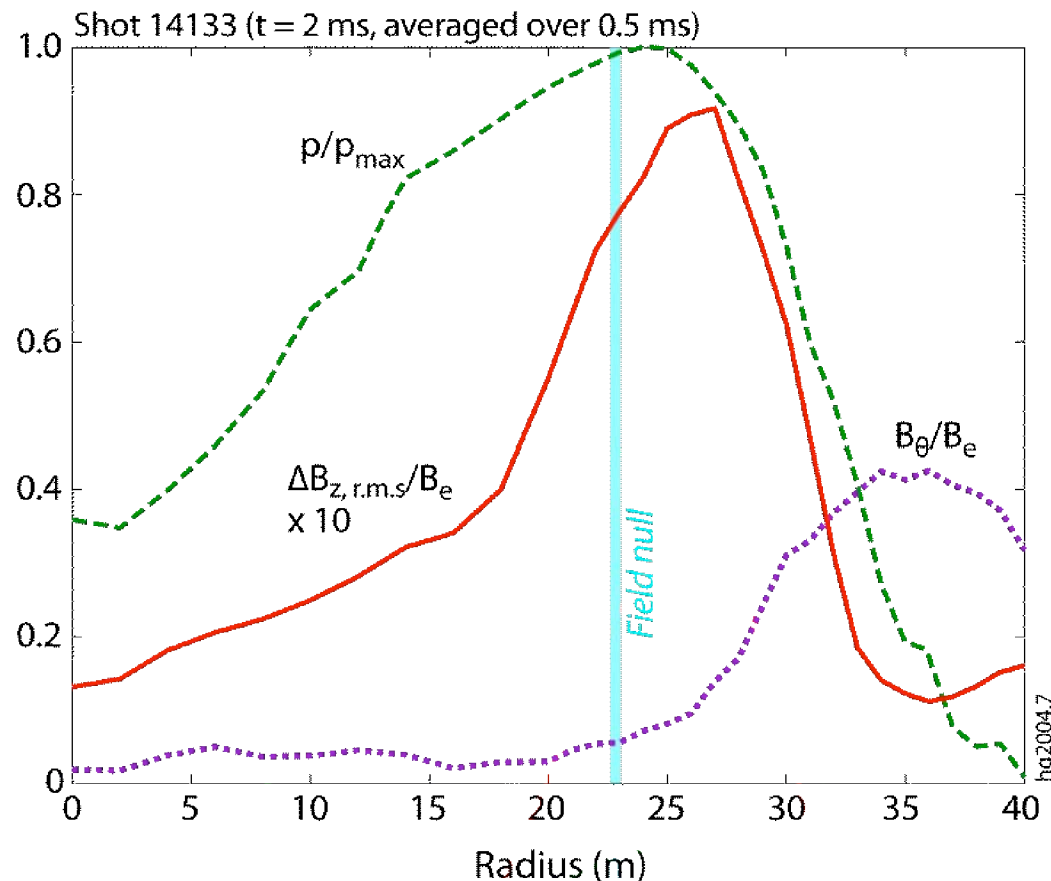# n=2 mode seen by tomography

No n=2
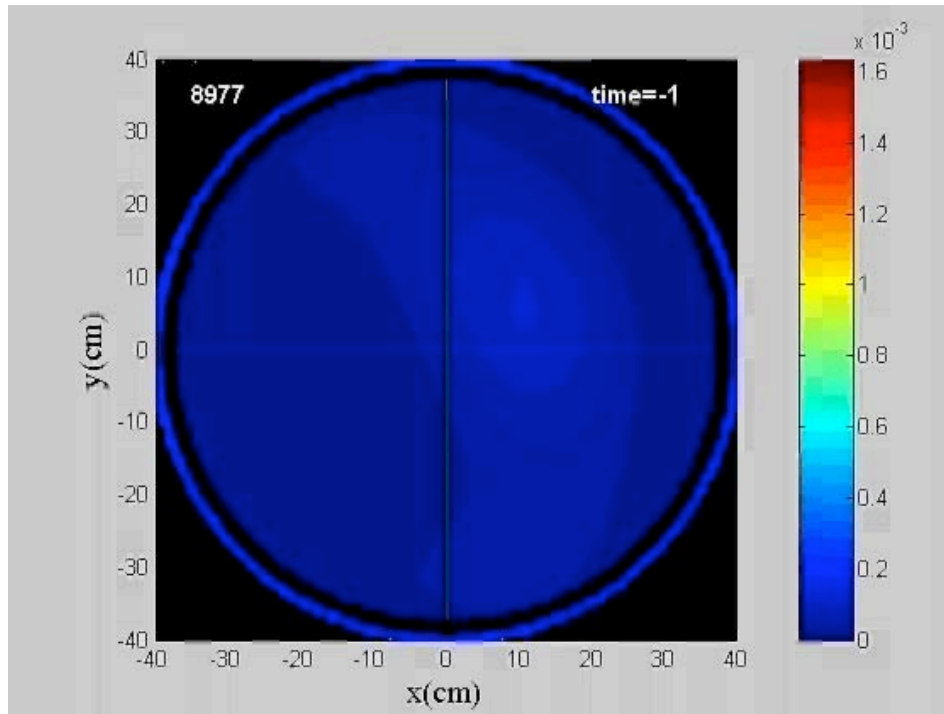
With n=2

- **n=2 mode** **rotates in the** **electron diamagnetic direction**, **in the same direction as RMF.**

Internal structure of n=2 modes

Shot 9062 (with low pass filter @ 50kHz)

Shot 9062 (t = 1.0 -1.5 ms)

- **n=2 distortions are localized outside the field null, $\omega_{n=2} = \omega_i$, $k_z = 0$.**
- **Driven by ion rotation outside field null** *where centrifugal force is in the same direction as the pressure gradient force.*

RMF stabilization

Shot 14133 (t = 2 ms, averaged over 0.5 ms)

p/p_{max}

$\Delta B_{z, r.m.s}/B_e$ x 10

Field null

B_θ/B_e

hg2004.7

Radius (m)

- **Oscillations are significantly reduced at edge where RMF is strong.**

- **Can be completely suppressed by keeping the separatrix radius r_s sufficiently close to the wall.**

➢ *We surmise that the radial force imposed by RMF provides stability to rotational modes by counteracting centrifugal force due to plasma rotation.*

Simple theory for RMF stabilization (*applicable to any plasma column*)

- **Rayleigh-Taylor analysis**

$$\_ \sim \_(r)\, e^{i(n\theta - \omega t)}$$

$$\gamma \approx (g/\delta_\rho)^{1/2}$$

- **Radial force due to RMF**

$$F_r = 2B_\omega^2/(\mu_0\_*)\,(r_s/r)\,e^{-2[(rs-r)/\_*]}$$
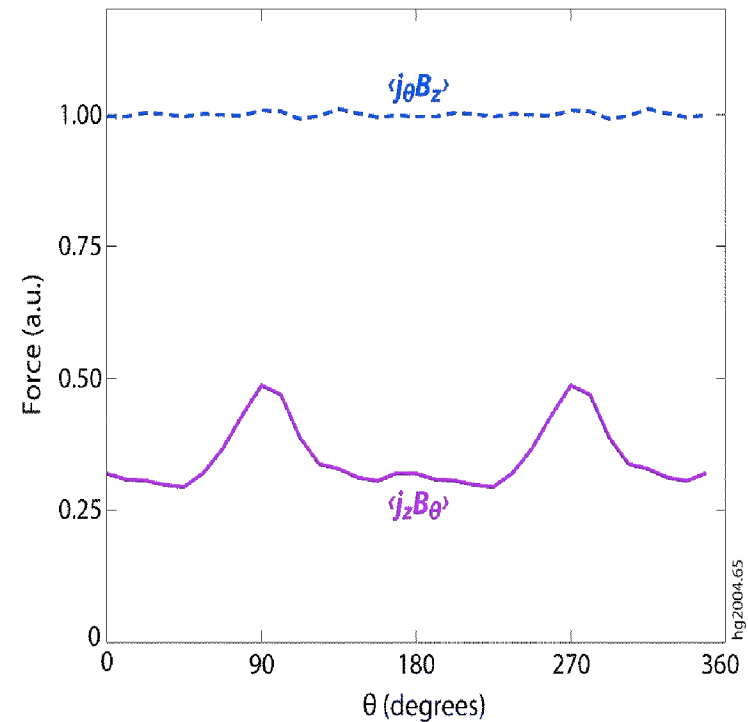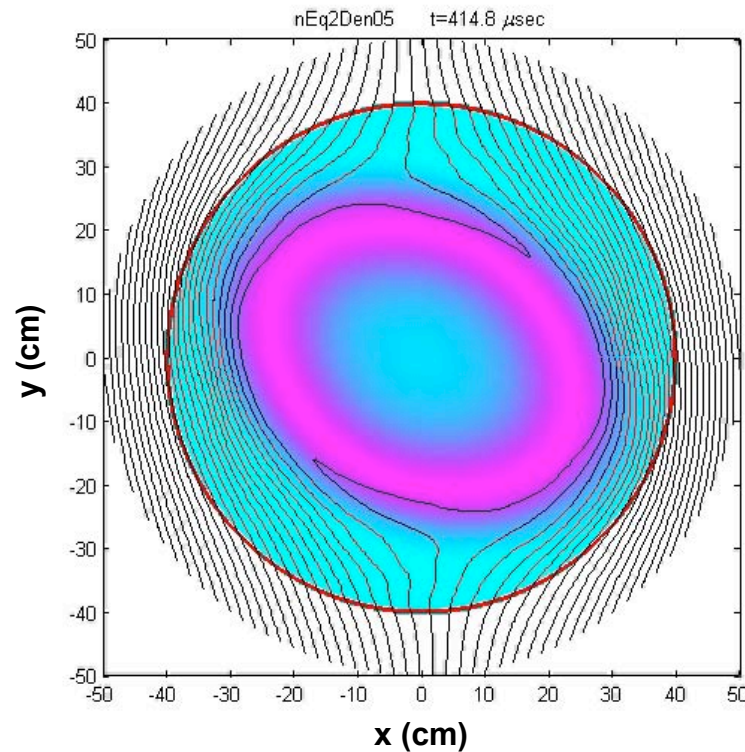
- **Effective growth rate**

$$\gamma = (\Omega^2 r/\delta_\rho - F_{r1}/\rho\_)^{1/2}, \quad F_{r1} = F_r\_/r_s$$

- **Stability threshold**
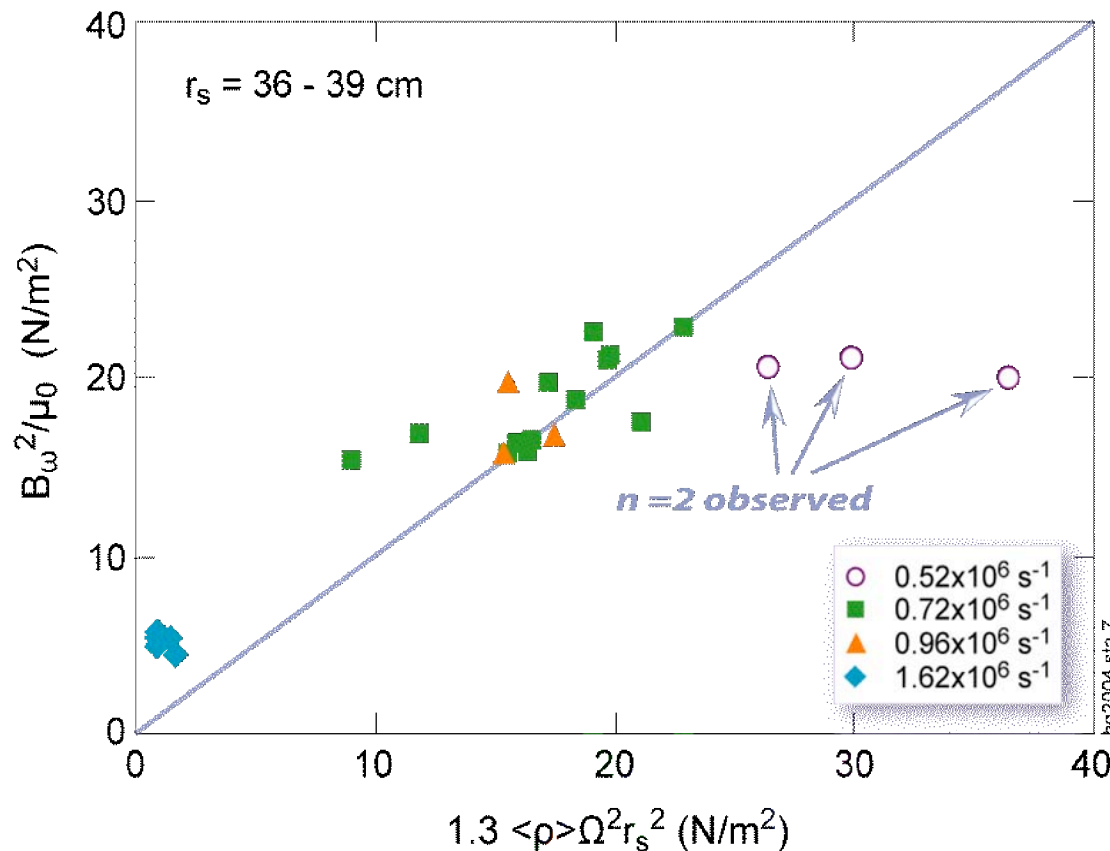
$$\Rightarrow B_\_^2/\_0 \geq 1.3\,\langle\rho\rangle\Omega^2 r_s^2$$

2D (r,_) simulation – with fixed stipulated elliptical distortion

nEq2Den05   t=414.8 μsec

- **Inward force due to RMF** $\langle j_z B\_ \rangle$ **changes as FRC column distorts**
 *exerting stronger force as plasma column extends outwards.*

Stability diagram

r_s = 36 - 39 cm

B_ω^2/μ_0 (N/m^2)

$n = 2$ observed

○	0.52x10^6 s^{-1}
■	0.72x10^6 s^{-1}
▲	0.96x10^6 s^{-1}
◆	1.62x10^6 s^{-1}

hg2004.sta.7

1.3 $\langle\rho\rangle\Omega^2 r_s^2$ (N/m^2)

RMF Stabilization criterion is satisfied for most FRCs except for the lowest ω, which produced the highest densities, pushing the centrifugal force beyond the instability threshold.

➤ *RMF stabilization also has significant implications for other quasi-linear confinement configurations, such as mirrors, which are intrinsically unstable to interchange/fluting modes.*
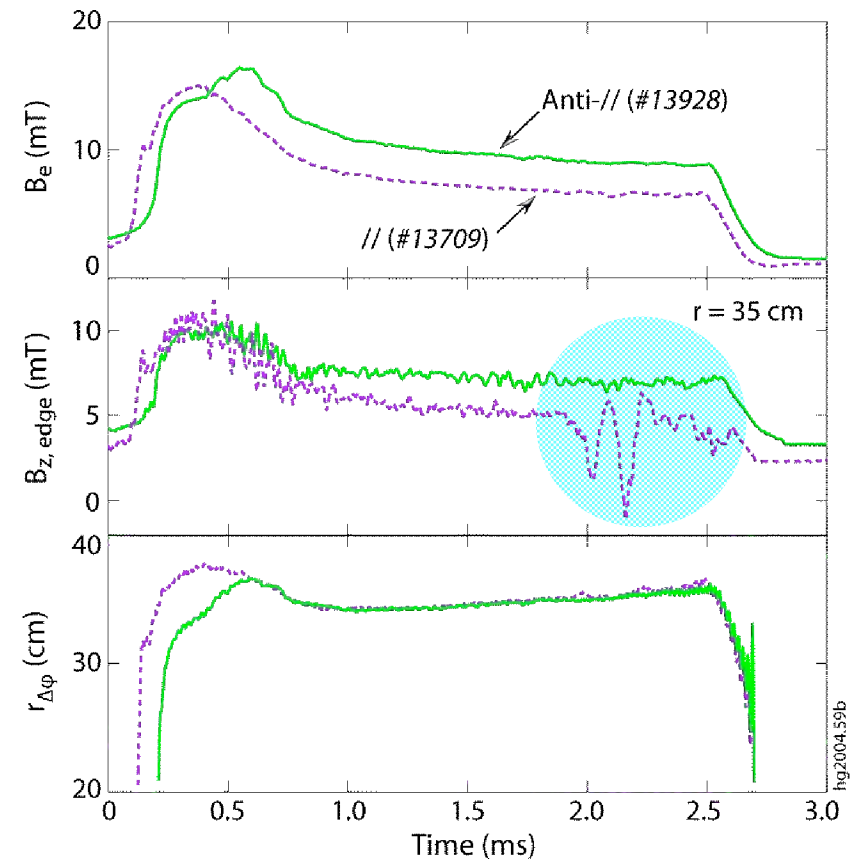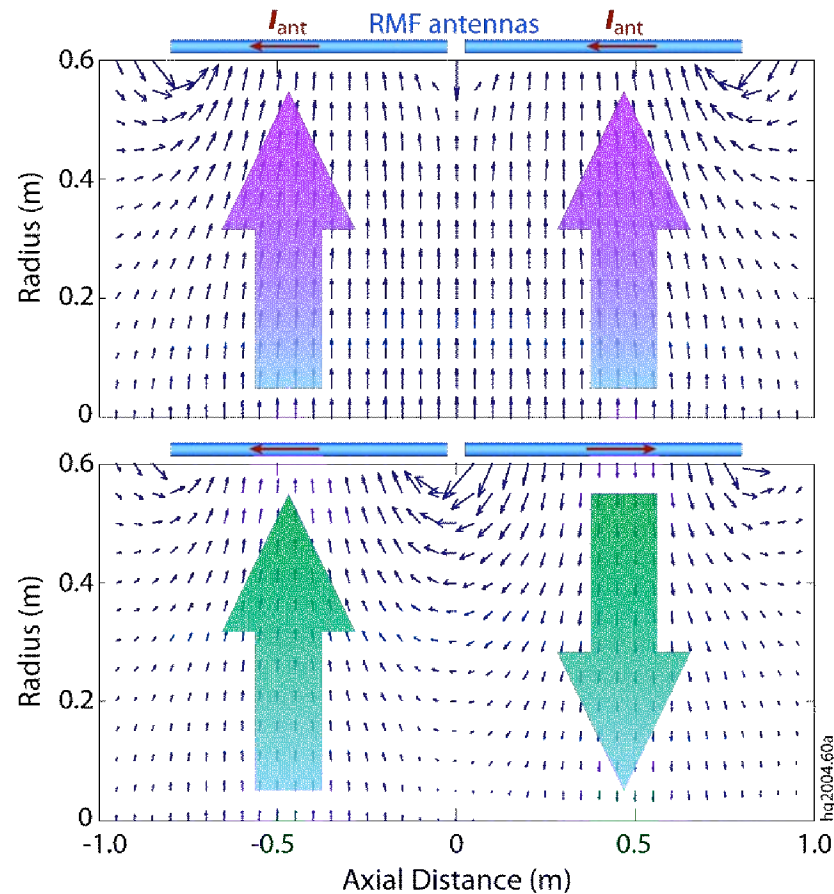
Localized central RMF drive
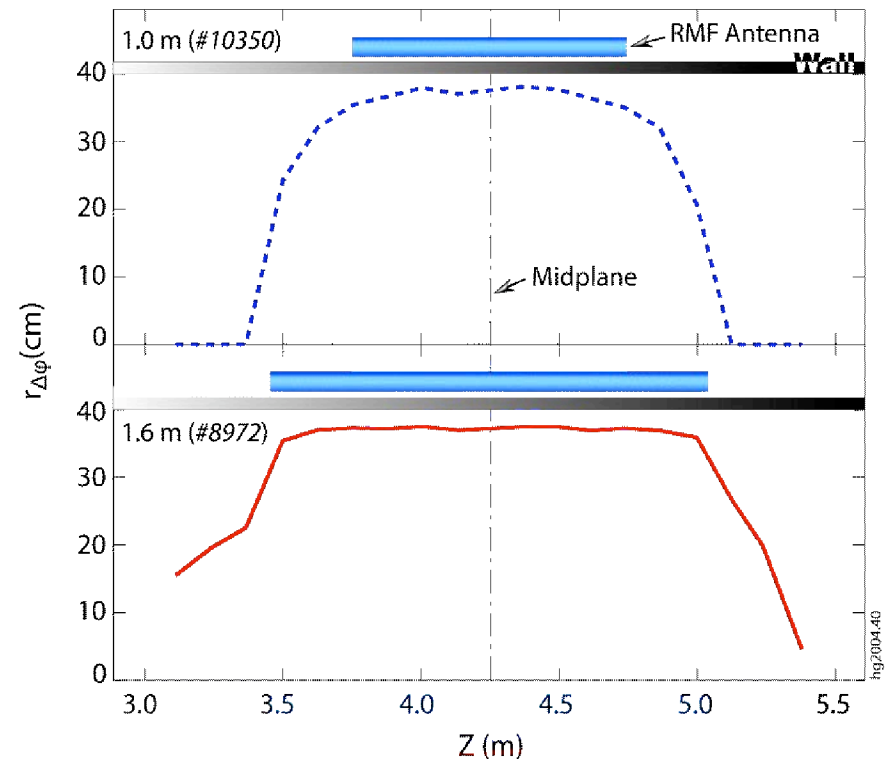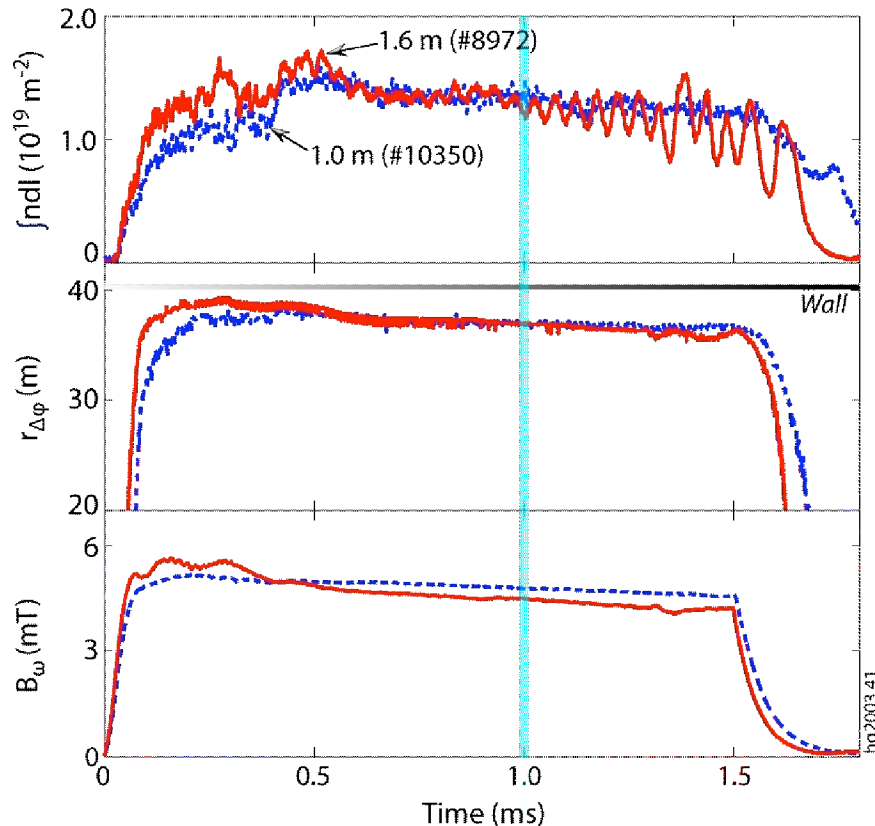
- **Operation with shorter antennas was less prone to n=2 mode.**
- **Plasma at ends rotates at a slower rate with a strong flow shear: $dV_\theta/dz \sim 10^5 \ s^{-1} \sim 0.4 \ kV_A$, which may be stabilizing.**

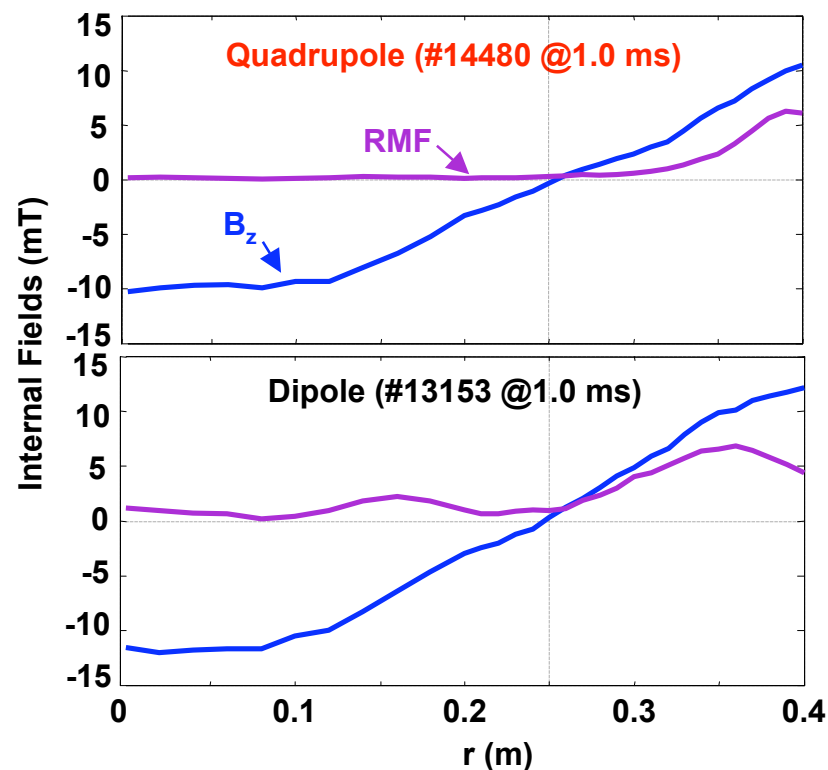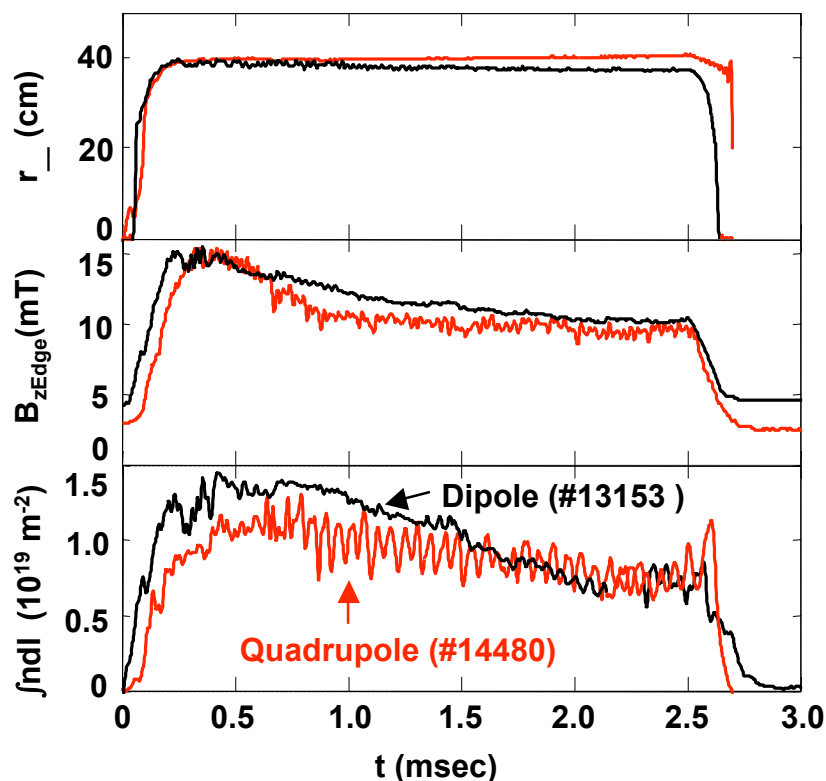 *Stabilization threshold for a sheared flow Z-Pinch is 0.1 kV_A*

Effect of anti-// RMF configuration

- **Anti-// RMF proposed by Cohen-Milroy as means of keeping even the edge fields closed.**

- **Also appeared to be even more stabilizing to rotational instabilities.**

Quadrupole RMF proposed as even better stabilization geometry – *it wasn't!*

- Quadrupole RMF formed FRCs and drove currents just as well as normal dipole antennas *(R.D. Milroy, this meeting).*

- But, less efficient in stabilizing the n=2 mode, possibly due to insufficient RMF near the field null where centrifugal force is strong.

Possible effect on tilt mode

RMF
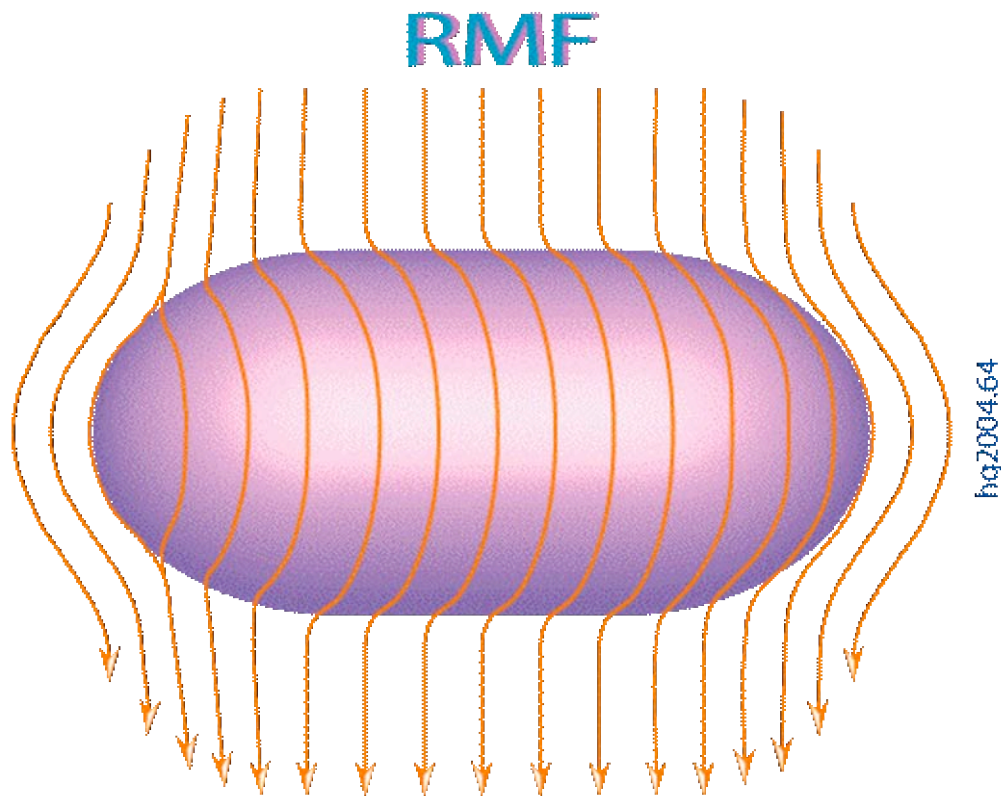
- **No tilt modes have been observed** for FRCs lasting over 500 tilt growth times:
  $$1/\gamma_{tilt} \sim \lambda_s/2V_A \sim 20 \text{ μs}$$

- **RMF may also have some influence on tilt stability** since it can act somewhat inside the separatrix.

- **Axial variation in RMF fields seem to be beneficial** in experiments with both shorter antenna lengths and anti-parallel antennas.

Kinetic effects are not important as T_i is low.

Summary & conlcusions

- **As in conventional θ-pinch formed FRCs, rotational modes have been observed in RMF formed FRCs with $\omega_{n=2} = \omega_i$.**

- **Rotational instabilities are localized near the field null, significantly reduced at the edge where RMF is strong.**

- **Can be further reduced by the use of either anti-// or centralized RMF current drive.**

- **In contrast, FRCs produced by the quadrupole RMF are more prone to rotational instabilities.**

- **No tilt instability has been observed in RMF driven FRCs with the configuration time lasting over 500 τ_{tilt} − *RMF may be also stabilizing to the tilt instability.***